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Radar Scan Strategies for the Patrick Air Force Base Weather Surveillance Radar, Model-74C, Replacement

David Short
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June 2008

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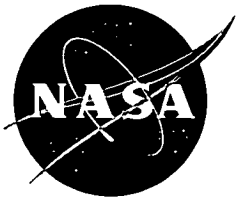

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Executive Summary

The 45th Weather Squadron (45 WS) is replacing the Weather Surveillance Radar, Model 74C (WSR-74C) at Patrick Air Force Base (PAFB), with a Doppler, dual polarization radar, the Radtec 43/250. A new scan strategy is needed for the Radtec 43/250, to provide high vertical resolution data over the Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) launch pads, while taking advantage of the new radar's advanced capabilities for detecting severe weather phenomena associated with convection within the 45 WS area of responsibility. The Applied Meteorology Unit (AMU) developed several scan strategies customized for the operational needs of the 45 WS. The AMU also developed a plan for evaluating the scan strategies in the period prior to operational acceptance, currently scheduled for November 2008.

The 45 WS provided the following operational requirements and comments that affect the radar scan strategy:

- The volume scan must update every 3 minutes or less; less than 2.5 minutes is desired.
- High vertical resolution reflectivity data are needed in the layer where the atmospheric temperature ranges from +5C to -20C,minus and plus 2 standard deviations, respectively. This corresponds to an altitude range of 7000 to 27,000 ft.
- The largest vertical spacing between radar beams in the altitude range specified above, within 5 n mi of the KSC/CCAFS space launch complexes, should be $\leq$ 2250 ft; < 1500 ft is desired,
- Excellent coverage of the boundary layer in and around CCAFS/KSC,
- Vertical spacing between radar beams independent of range at a given altitude is desired.

The 45 WS requires rapid weather radar updates, every 3 min or less, of 3-D volume scans for evaluating Lightning Launch Commit Criteria (LLCC) and monitoring the growth and electrification of convective clouds. Excellent coverage of the boundary layer is needed to detect low level boundaries such as sea breeze fronts, river breeze fronts, convective outflows, and others, which are vitally important to thunderstorm prediction in central Florida during the summer. Radar products generated by the new data processing system will be used by forecasters of the 45 WS, SMG and NWS MLB to provide weather warnings and watches for convective wind events such as downbursts and mesoscale vortices which can spawn tornadoes.

The AMU compared three scan strategies, each designed to meet requirements established by the 45 WS. A scan strategy designed by the 45 WS and refined in consultation with the AMU was found to provide a 33% improvement in vertical gaps over the space launch/landing facilities of KSC/CCAFS, compared to the current WSR-74C scan strategy. The 45 WS scan strategy is recommended for operations, pending a satisfactory evaluation when the new radar is installed and operating.

The AMU also evaluated several other characteristics of radar performance that affect the overall scan strategy: These included the following:

- Doppler Dilemma, jointly constraining maximum range and maximum Doppler radial velocity.
- Number of samples for Doppler processing depending on antenna rotation rate and pulse repetition frequency.
- Radar duty cycle constraining jointly the pulse length and pulse repetition frequency.
- Radar sensitivity increasing with increasing pulse length.
- Compatibility of Doppler and dual polarization modes in terms of signal processing techniques that can improve radar products.

The AMU outlined a plan for evaluating scan strategies with special emphasis on the following:

- Time required to complete a volume scan
- Time required for product generation and transmission;
- Effect of vertical spacing between radar beams on product display and interpretation

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1. Introduction

The 45th Weather Squadron (45 WS) is replacing the Weather Surveillance Radar, Model 74C (WSR-74C) at Patrick Air Force Base (PAFB) with a Doppler, dual polarization radar, the Radtec 43/250. This new radar will be located 23 n mi WSW of Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS). A new scan strategy is needed to take advantage of this radar's advanced capabilities for detecting severe weather associated with convection within the 45 WS area of responsibility, while providing high vertical resolution data over and around the KSC/CCAFS launch pads. Rapid updates are required for evaluating Lightning Launch Commit Criteria (LLCC), space shuttle Landing Flight Rules and monitoring the growth and electrification of convective clouds. Excellent coverage of the boundary layer is needed to detect low level boundaries that are so vital to thunderstorm formation in this area during the summer.

Radar products generated by the new data processing system will be used by forecasters of the 45 WS, Spaceflight Meteorology Group and the National Weather Service office in Melbourne, FL (NWS MLB). The new radar will also provide capabilities to detect cloud electrification, improving the timeliness of lightning advisories and maintaining the capability for evaluation of LLCC. Improved detection and prediction of severe weather from the new Doppler capability and improved downburst wind prediction from the new dual polarization capability should also result from the new radar. The Applied Meteorology Unit (AMU) evaluated the capabilities of the new weather radar and developed scan strategies customized for the operational needs of the 45 WS. The AMU also developed a plan for evaluating the scan strategies in the period prior to operational acceptance, planned for February 2009. The 45 WS will use the results of the evaluation to choose one or more of the scan strategies developed by the AMU.

1.1 Volume Scan Requirements

The 45 WS has defined four operational requirements that affect the radar scan strategy:

1) The volume scan must update every 3 min or less, and less than 2.5 min is desired. The current WSR-74C update cycle is 2 min 40 s, with a scan rate of 6 revolutions per minute (rpm) and 12 elevation angles. Approximately 3 s are required for the antenna to stabilize from one elevation angle to the next. The new antenna is capable of providing up to 18 elevation angles during a 3-min volume scan. Antenna stabilization requires 2.5 s. Therefore, a sequence of consecutive 360° scans at 12 different elevation angles can be completed in 2.5 min. A volume scan comprised of 13 elevation angles can be completed in 2 min and 42.5 s.
2) High vertical resolution reflectivity data are needed in the layer where the temperature ranges from +5°C to -20°C, including +/- 2 standard deviations. High vertical resolution is accomplished by having as many elevation angles in the scan strategy as possible while avoiding overlap and not exceeding the volume scan rate requirement. Climatological data from the Range Reference Atmospheres, provided by the Range Commanders' Council Meteorology Group (Henning and Roberts 2006) shows the corresponding altitude range is from about 7000 to 27,000 ft (Short 2000).
3) The largest vertical spacing between beams within 5 n mi of the KSC/CCAFS launch complexes should be $\leq$ 2250 ft, and $<$ 1500 ft is desired. The current WSR-74C scan strategy provides an average vertical spacing of 2020 ft over the altitude interval from 10,000 to 25,000 ft in the range interval from 9 to 60 n mi (Short 2000). Radar beam width also plays a role in determining vertical gaps, with a wider beam width resulting in smaller gaps. The beam width of the new radar is 0.95°, about 10% less than the WSR-74C at 1.05°. The desired vertical spacing requires a customized sequence of elevation angles.
4) Excellent coverage of the boundary layer is required to detect low level boundaries that drive much of the thunderstorms in central Florida during the summer.
5) Equal vertical spacing between beams is desired. The current WSR-74C scan strategy provides vertical gaps that are nearly constant with range, at a given altitude. This design provides a sampling of the structure of storms that is almost independent of their distance from the radar.

The 45 WS has also provided amplifying remarks on scan strategy criteria to the following effect:

> The scan strategy should provide excellent coverage of reflectivity and dual polarization parameters from 5400 to 27,000 ft in altitude over KSC/CCAFS, especially over the launch pads approximately 23 n mi northeast through east-southeast of the radar. Vertical gaps should be less than 2250 ft between beams from 8200 to 27,000 ft in altitude within 5 n mi of the pads. There should be good vertical coverage up to 40,000 ft within 10 n mi of the launch pads. Up to 45,000 or even 50,000 ft is preferred, if that can be done within the volume scan time limit. Excellent coverage of low level boundaries (surface to 5000 ft) within 25 n mi of the radar is desired, especially around the coastline and around the Banana and Indian River Lagoons. Ground clutter suppression will be vital with a lowest scan angle as low as 0.2°. Excellent Doppler coverage is needed to detect severe weather events in storms approaching from the southwest through northwest. Outstanding severe weather coverage is desired within 20 n mi of the edge of the KSC/CCAFS property. The radar cone of silence should be reduced as much as possible. General surveillance scans should provide coverage out to 60 n mi.

1.2 Radar Characteristics

Figure 1 shows the proposed location of the new radar, 20 n mi northwest of the existing WSR-74C site at PAFB and about 23 n mi WSW of the launch complexes on KSC and CCAFS. This site also allows coverage of PAFB, which the current WSR-74C radar cannot provide since it is located at PAFB, putting its cone of silence directly over the base.

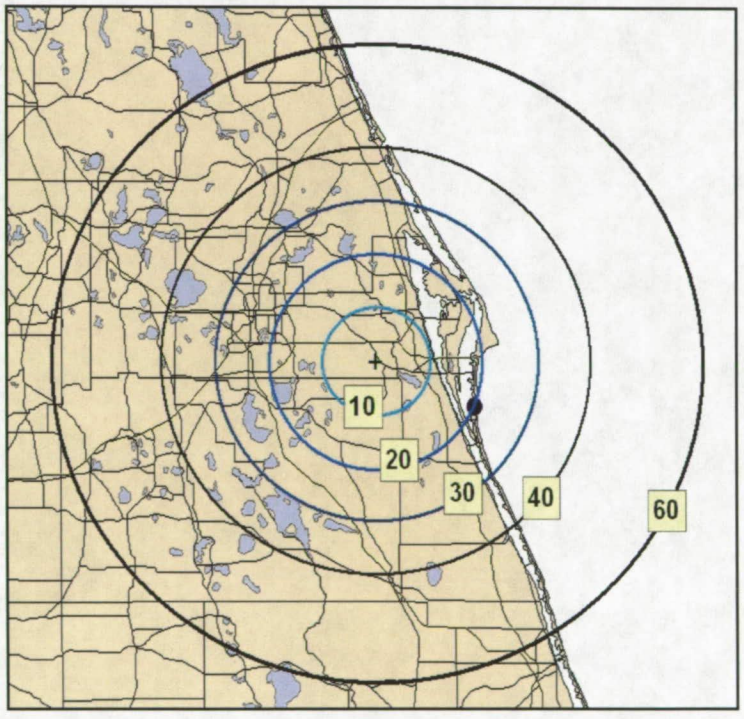

Figure 1. Locations of the new Doppler, dual polarization radar (+), and the existing WSR-74C radar on PAFB (•). Range rings are at 10, 20, 30, 40 and 60 n mi from the new radar.

Table 1 lists characteristics of the new radar that determine limitations to its performance. These are discussed briefly here and in detail in Sections 2, 3 4, and 5. The fully coherent Klystron transmitter simultaneously transmits horizontal and vertically polarized pulses, allowing a full suite of dual polarization data and products, detailed in Section 5. The C-band frequency is attenuated in heavy precipitation; however, it allows a relatively small antenna that can be rotated rapidly and generates a pencil beam (< 1° beam width). The antenna can operate continuously with a rotation rate of 6 rpm. The peak power of 250,000 Watts and the maximum average power of 1,250 Watts combine to give the radar an average duty cycle of 0.005, the fraction of each second that the transmitter is actually

on. In operational use, a maximum duty cycle of 0.003 is recommended by the vendor. The maximum duty cycle restricts the available combinations of pulse length and pulse repetition frequency (PRF). The maximum sensitivity surpasses that of the WSR-74C by about 20 dBZ, where dBZ = 10 × $Log_{10}(Z_e)$, and Z_e is the equivalent radar reflectivity. This provides improved capabilities for detecting sea breeze and outflow boundaries, chaff, anvil clouds and very light precipitation. The offset feed antenna has very low side lobes, permitting a lowest elevation angle of 0.2° and excellent capabilities for detecting low-altitude phenomena such as mesoscale vortices, and sea breeze and outflow boundaries.

Table 1. Radtec 43/250 Radar Characteristics

Parameter	*Value*
Transmitter	Fully coherent Klystron
Frequency (wavelength)	5.6 GHz (5.36 cm)
Peak power	250,000 Watts
Maximum average power	1,250 Watts
Duty cycle	0.005 (maximum); 0.003 (recommended)
Pulse Repetition Frequency	200 to 2,000 pulses per second
Pulse width	0.5 to 10 microseconds
Maximum Sensitivity	-12 dBZ at 60 n mi range with a 2 microsecond pulse length
Antenna	Offset feed (4.3 m diameter)
Beam width	0.95 °
Maximum Rotation rate	6 rpm
Stabilization time	2.5 s

2. Volume Scan Timing

The Radtec 43/250 radar antenna can be used operationally with a rotation rate of 6 rpm, resulting in one 360° sweep every 10 s. To calculate the time to complete a volume scan, one must take into account the number of elevation angles and a 2.5 s interval required for the antenna to stabilize when changing from one elevation angle to another. Figure 2 illustrates the maximum number of elevation angles that can be scanned in 3 min with these characteristics. The first 12 of the 15 scans are completed in 2.5 min, and another 12.5 s are required to complete the 13th scan. Experience with the WSR-74C has shown that at least 12 elevation angles are needed to provide the vertical resolution requirements outlined in Section 1.1. In addition, the 45 WS desirable requirement for updating the volume scan is every 2.5 min. However, the 45 WS has indicated that having 13 elevation angles to improve the vertical resolution is an acceptable trade-off for the increase in volume scan time beyond 2.5 min.

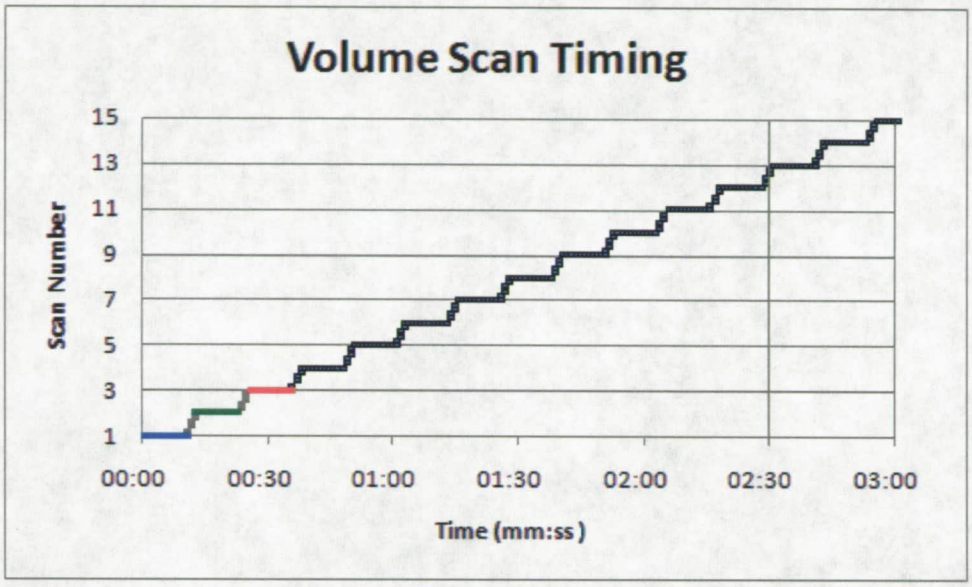

Figure 2. Time versus scan number for an antenna rotation rate of 6 rpm and an antenna stabilization time of 2.5 seconds. The first three complete 360 scans are color coded in blue, green and red, respectively. Twelve scans are completed in 2 min and 30 s.

Figure 3 shows a schematic of the 3-D sampling provided by the first three elevation angles in a volume scan. The sequential elevation angles are indicated blue, green and red as in Figure 2. The product generation software uses interpolation procedures to fill in horizontal and vertical gaps between the radar beams. The interpolated products provide the analyst with map-like views of storms to chart their location and motion, and vertical cross sections to monitor their rates of growth and decay.

An interleaved scan is used to reduce wear on mechanical pedestal systems driving the antenna. For a numbered sequence of increasing elevation angles, the odd numbered ones are scanned first as the elevation increases. The even numbered ones are scanned as the elevation decreases. Figure 4 illustrates an interleaved scan with 13 elevation angles.

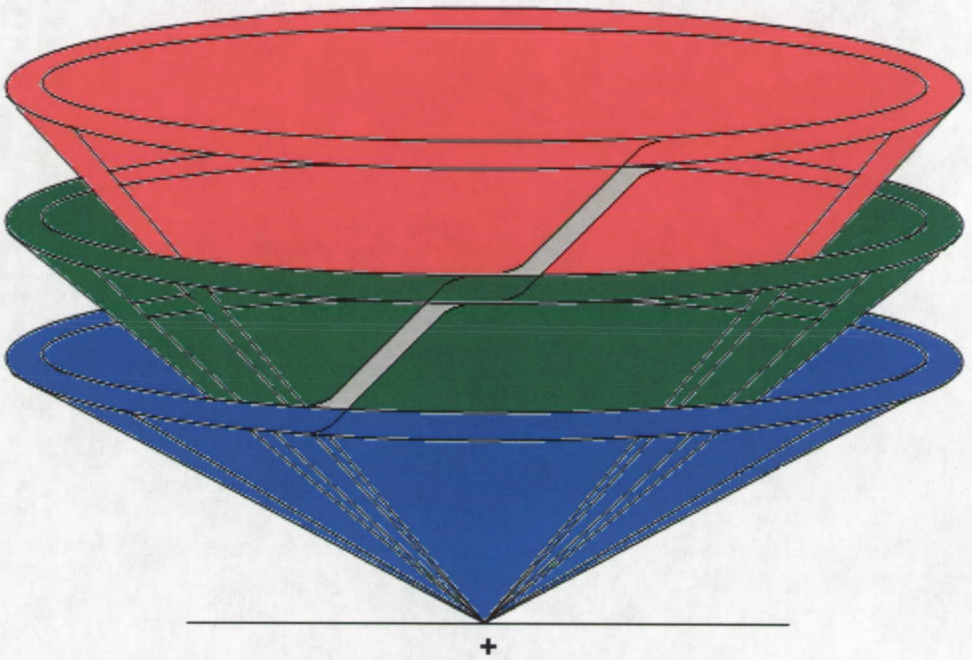

Figure 3. A 3-D schematic representing the radar coverage by provided by three 360° scans with antenna elevation changes shown as grey ramps.

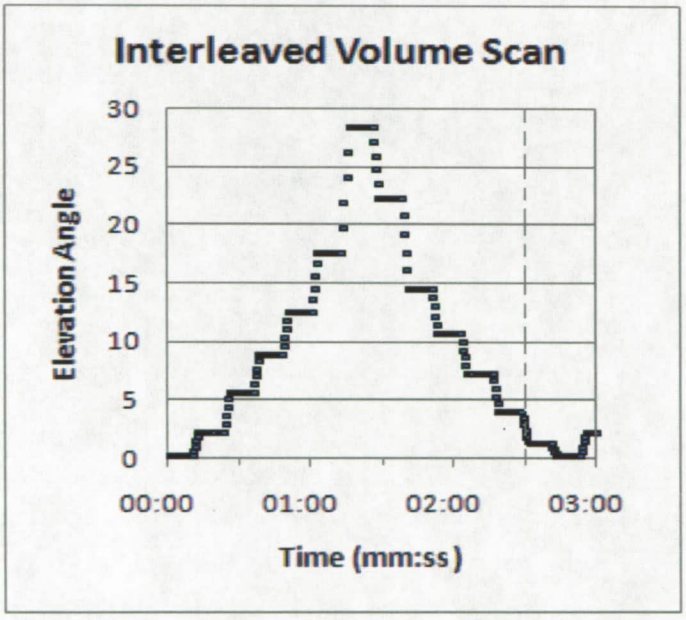

Figure 4. Time versus elevation angle for an interleaved volume scan. The interleaved volume scan has 13 elevation angles, with an antenna rotation rate of 6 rpm and stabilization time of 2.5 s. The dashed vertical line denotes 2.5 min. This volume scan is completed in 2 min 42.5 s.

3. Vertical Resolution

The vertical resolution, as defined here, is determined by the angular spacing between adjacent elevation angles and the radar beam width. This is demonstrated in Figure 5, which shows the radar beams from adjacent elevation angles in cross-section. The vertical gap, G, is shown at range R and altitude A.

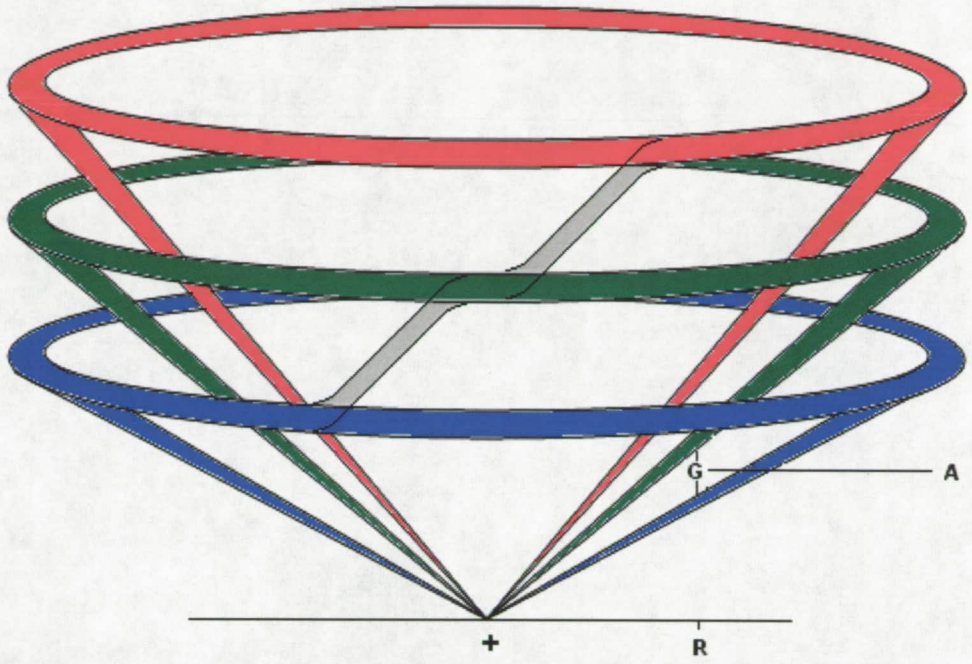

Figure 5. A schematic of radar beams from adjacent elevation angles. The vertical gap G is shown at range R and altitude A.

3.1 Objectives

The objective in choosing a sequence of elevation angles for a scan strategy was to have vertical gaps that satisfied as many of the requirements listed in Section 1.1 as possible. Three scan strategies are described and compared in this section: 1) provided by Radtec Engineering, Inc. and based on 45 WS guidelines, 2) a refinement of the Radtec scan by the AMU, based on further consultation with the 45 WS, and 3) an AMU design that is similar to the existing WSR-74C scan, but with one additional elevation angle.

3.2 Vendor

The 45 WS supplied Radtec Engineering, Inc. with an initial list of requirements in September 2007. These included the first three points of Section 1.1, plus the following broader guidelines intended to familiarize the 45 WS with the radar's full range of capabilities:

- Vertical coverage up to 40,000 ft within 10 n mi of KSC/CCAFS launch pads; up to 50,000 ft desirable
- Highest elevation angle of 36 to 40° to reduce the radar cone-of-silence
- Option for maximum range to 60 n mi, if 120 n mi range cannot be done within 3 min
- Excellent coverage of low-level boundaries, < 5000 ft, within 25 n mi of the radar, starting with a beam angle as low as 0.2°, if justified.
- Moderate to long pulse to mitigate the loss of sensitivity due to attenuation through heavy thunderstorms

Figure 6 shows a vertical cross-section of the beam coverage provided by the first 13 elevation angles of the scan strategy designed by Radtec Engineering, Inc. in response to the initial 45 WS guidelines. The scan strategy provides an excellent first-guess solution to minimizing vertical gaps to <2250 ft over the KSC/CCAFS launch pads.

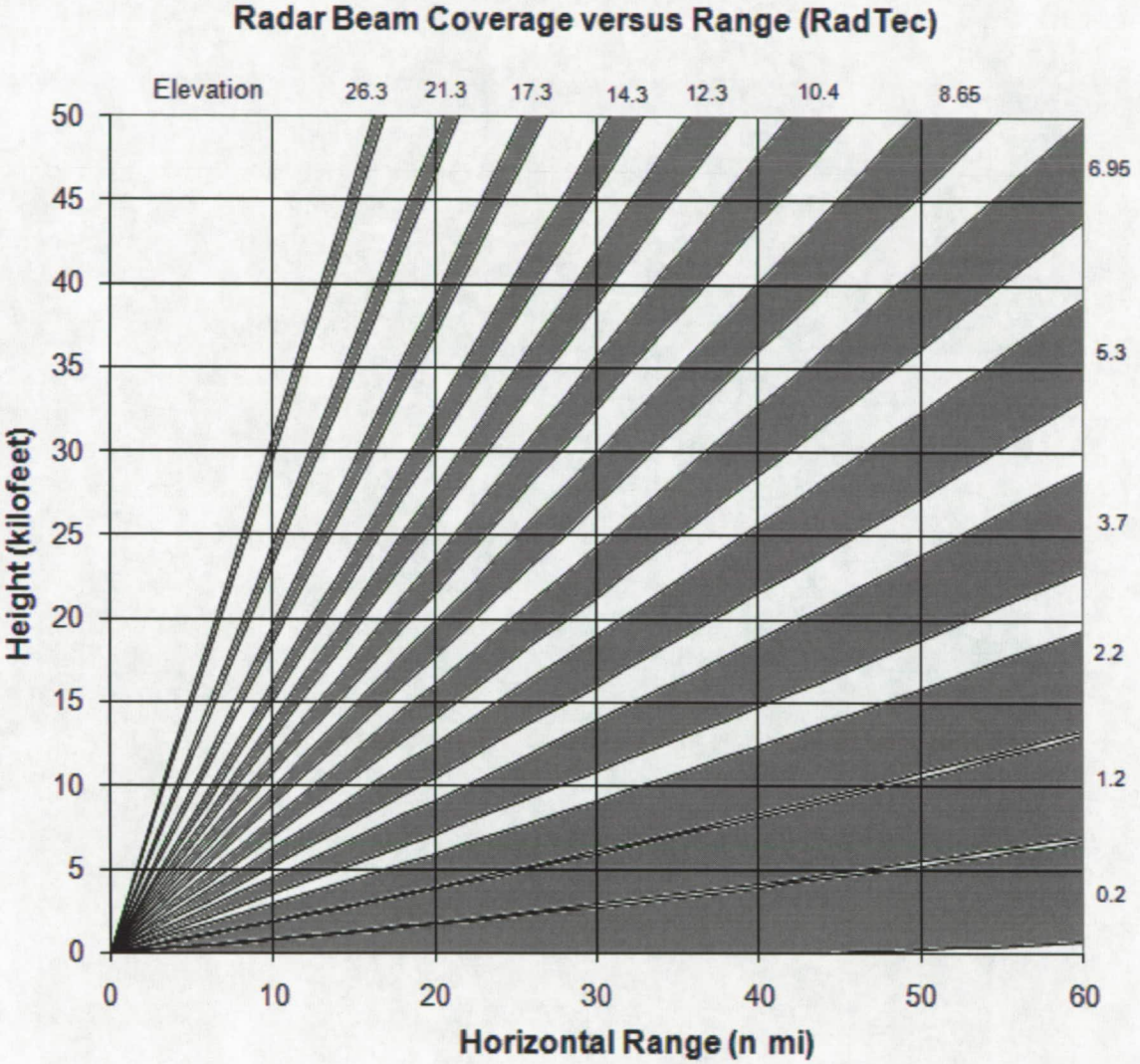

Figure 6. Range-height cross section of beam coverage for a first-guess scan strategy developed by the radar vendor, Radtec Engineering, Inc.

3.3 45 WS

Mr. Roeder (45 WS) presented the possibility of a single scan strategy that could satisfy the requirements for vertical coverage and LLCC evaluation during both warm and cool seasons. The key to this simplification involves requirements for monitoring rapidly building cumulus when their tops reach the +5°C isotherm, predominantly a warm season phenomenon, and requirements for monitoring thick layered clouds, predominantly a winter phenomenon, when any part of the cloud layer is colder than 0°C. The simplification is possible because the lowest height of the 0°C isotherm observed in the cool season is 9000 ft, close to the lowest height of the +5°C isotherm during the warm season, 10,000 ft. The resulting scan strategy is based on the time sequence of elevation angles shown in Figure 4, producing a beam coverage pattern that minimizes vertical gaps within 5 n mi of the launch complexes on KSC and CCAFS, which are approximately 23 n mi from the radar.

Figure 7 shows a range-height cross section for these elevation angles. The critical altitude range for evaluating

LLCC is from about 7000 to 27,000 ft. The requirement for vertical gaps is 2250 ft or less because of the thick cloud rule that prohibits launch/landing trajectories through clouds having a thickness of 4500 ft or more, with any part of the cloud located between the 0°C and -20°C isotherms within 5 n mi of the launch complexes. This design ensures that at least two radar beams will sample a thick cloud within 5 n mi of the launch complexes if it has a thickness ≥4500 ft. The radar beams in Figure 7are shaded to indicate their beam width of 0.95°.

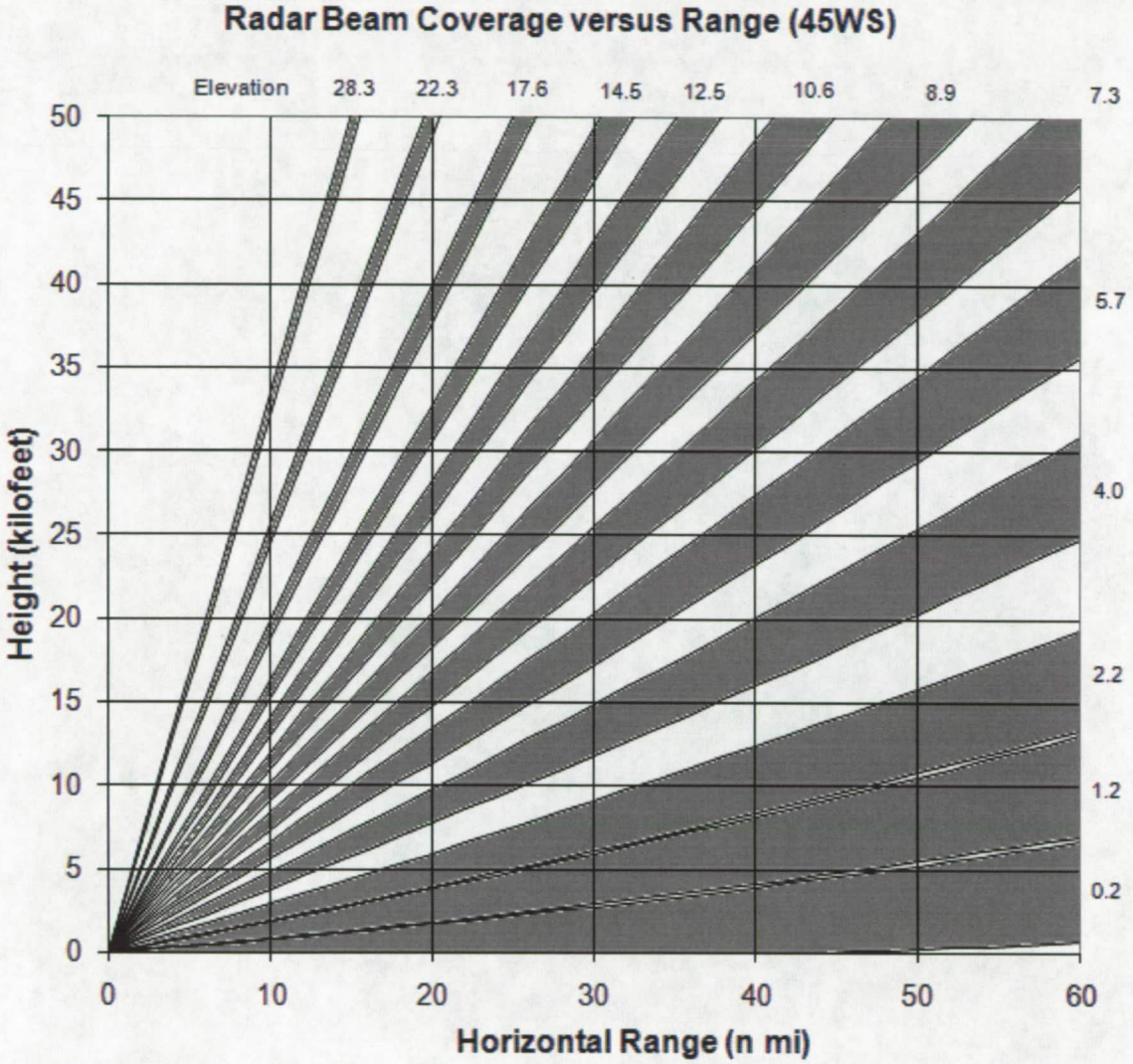

Figure 7. Range-height cross section of beam coverage for the 45 WS scan strategy using the elevation angles listed in Table 2.

Table 2 lists the elevation angles for the 45 WS scan strategy, and a description of the purpose for each elevation angle. The lowest elevation angle provides coverage of low level boundaries associated with sea-breezes and river-breezes, and outflows of cool, moist air from convective storms. The second and third elevation angles provide coverage of low-level vortices within severe convective storms that may be tornadic and low level boundary detection. The spacing of the intermediate angles is specifically designed to reduce vertical gaps between radar beams over the launch pads on KSC and CCAFS in order to improve evaluation of LLCC, especially the Thick Cloud LLCC. The highest elevation angles provide high altitude coverage of deep convective storms, especially the Anvil Cloud LLCC. The last elevation angle determines the radius of the cone-of-silence, the region above the radar where it cannot detect storms. A near-by radar, such as the WSR-88D at NWS MLB can be used to detect storms within the Radtec 43/250 cone-of-silence, and vice versa.

Table 2. Elevation angles for the 45 WS scan strategy.	
Elevation Angle (degrees)	***Purpose***
0.2	Low Level Boundary Detection
1.2	Low Level Boundary Detection and Low Level Vortex Detection
2.2	Low Level Vortex Detection and Low Level Boundary Detection
4.0	Reduce vertical gaps near pads
5.7	"
7.3	"
8.9	"
10.6	"
12.5	"
14.5	"
17.6	High altitude coverage, especially anvil clouds
22.0	High altitude coverage, especially anvil clouds
28.3	Reduce cone of silence and anvil cloud coverage

3.4 AMU

The AMU developed a third possible scan strategy by adding a 13th elevation angle to the AMU-designed WSR-74C scan strategy (Short 2000), lowering the lowest elevation angle to 0.2° and adjusting the higher elevation angles appropriately. Figure 8 shows a range-height cross section of beam coverage produced by the modified WSR-74C design, resulting in vertical gaps independent of range out to a distance of 50 n mi and above an altitude of 7000 ft. The average vertical gap produced by the beam pattern shown in Figure 8 is about 60% larger over the launch complexes than that produced by the 45 WS pattern shown in Figure 7. Because of these larger gaps, 45 WS prefers the previous scan strategy.

The advantage of the scan strategy in Figure 8 is that it would produce a more homogeneous spatial sample of raw data over the radar surveillance area compared to the Radtec and 45 WS designs. The raw data is automatically smoothed for display by the radar processing software, and the display is visually interpreted by the radar operator.

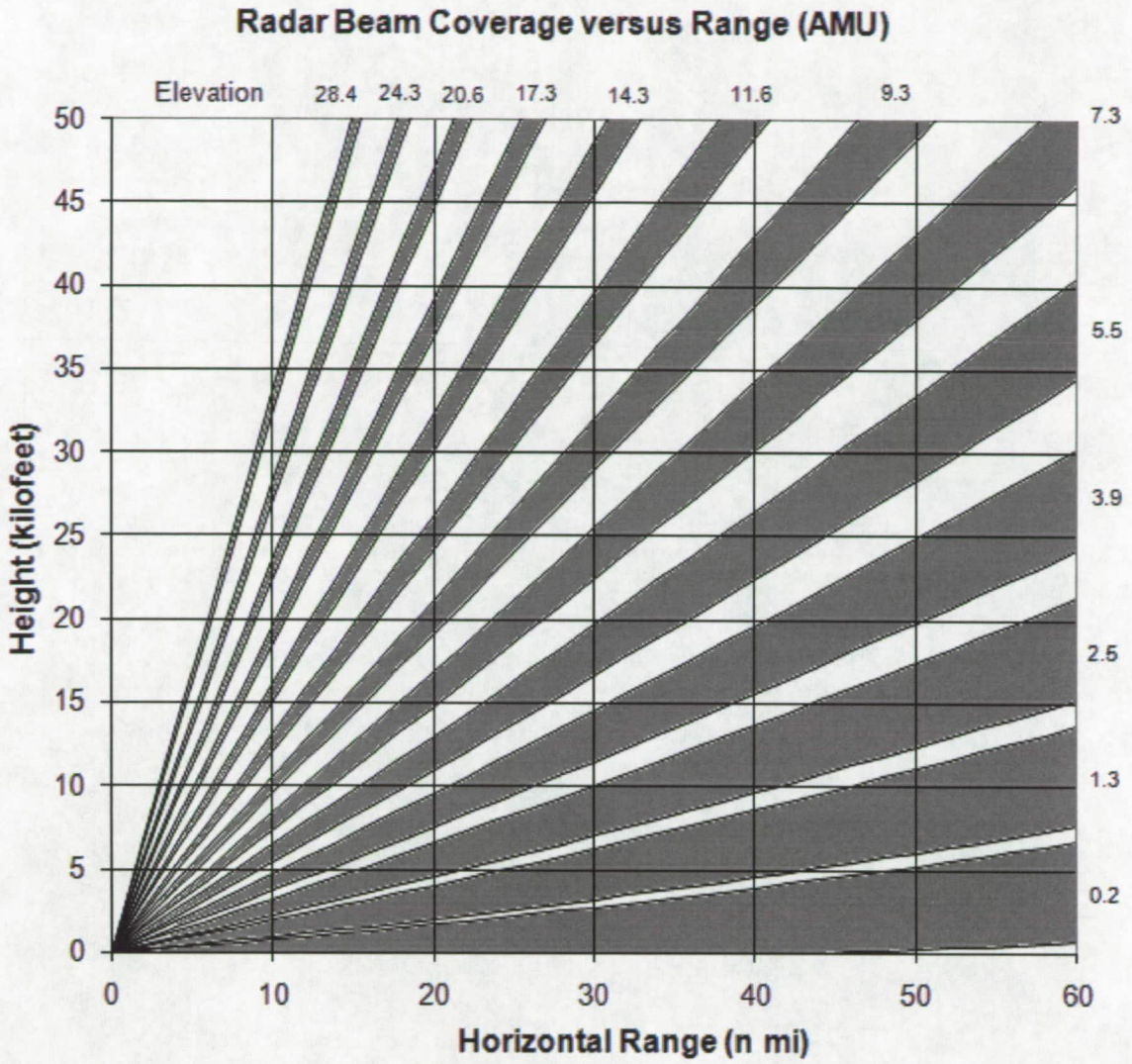

Figure 8. Range-height cross section of beam coverage for the AMU scan strategy, based on the current WSR-74C strategy, with one additional elevation angle.

3.5 Comparison of Vertical Gaps in the Radtec, 45 WS and AMU Scan Strategies

The size of vertical gaps between adjacent beams was used for an objective comparison of the three scan strategies presented above. The AMU determined vertical gaps by using the Radtec 43/250 half-power point beam width of 0.95°. The scan strategies were designed by first calculating gaps between the half-power points of adjacent beams at an altitude of 27,000 ft, near the upper limit of the -20°C isotherm over east-central Florida, and then by adjusting elevation angles to meet the 45 WS requirements outlined in Section 1.1. Elevation angles were specified to the nearest 0.1°. Because vertical gaps at lower altitudes are smaller, decreasing directly in proportion to altitude, the vertical gap criteria at all altitudes of interest will be met by satisfying it at the maximum altitude of interest.

Figure 9 shows a comparison of the vertical gaps at 27,000 ft for the three scan strategies, each comprised of 13 elevation angles. The Radtec and 45 WS designs shown in Figures 6 and 7, respectively, both have the objective of vertical gaps less than 2250 ft within 5 n mi of the launch complexes at KSC and CCAFS. Thus, the minima in vertical gaps over the corresponding range interval are from 18 to 28 n mi. The AMU scan strategy was designed to provide vertical gaps that are constant with range, at a given altitude. This comparison shows that the constraint of 13 elevation angles does not allow development of a scan strategy that meets requirements 3 and 4, a maximum vertical spacing of 2250 ft and equal vertical spacing, at the same time.

Vertical gaps decrease in direct proportion to decreasing altitude. Thus the vertical gaps at an altitude of 13,500 ft are half as large as those depicted in Figure 9. The average gaps over the altitude interval of 7000 to 27,000 ft are about 62% as large as those at 27,000 ft. For example, over the range interval from 18 to 28 n mi, the average vertical gaps from the 45 WS scan strategy are 0.62*2100 ft = 1302 ft. Over the same interval the AMU design has average vertical gaps of 2170 ft. A comparison of maximum vertical gaps over the 18 to 28 n mi range interval shows 2250 ft for the 45 WS scan strategy and 3750 ft for the AMU design.

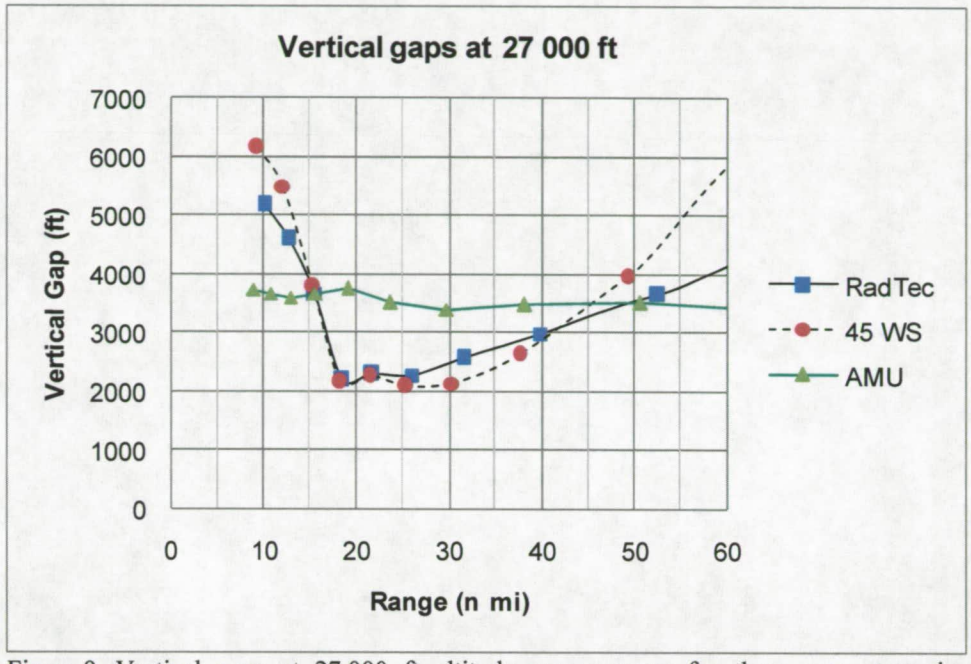

Figure 9. Vertical gaps at 27,000 ft altitude versus range for three scan strategies developed by 1) Radtec Engineering Inc. (blue squares), 2) the 45 WS (red circles), and 3) the AMU, following the WSR-74C design (green triangles).

4. Doppler and Other Considerations

A complete radar scan strategy must also take into consideration several constraints that are governed by signal processing, electronic, and mechanical factors. These include the "Doppler Dilemma", the number of samples available for reflectivity and Doppler radial velocity estimation, the maximum duty cycle that can be sustained by the radar transmitter, and the effect of pulse length on the radar sensitivity.

4.1 Doppler Dilemma

The Doppler Dilemma involves a dependence of the unambiguous maximum range and unambiguous maximum Doppler ***radial*** velocity on the pulse repetition frequency (PRF). The term "radial" is emphasized here because a Doppler radar estimates velocities toward or away from the antenna, not the full vector velocity. The maximum range decreases as the PRF increases, while the maximum Doppler radial velocity increases as the PRF increases, as shown in Figure 10. The term "unambiguous" indicates the range and radial velocity available by direct calculation, without additional radar and signal processing techniques (Doviak and Zrnic 1993). Figure 10 indicates that the maximum unambiguous Doppler radial velocity approaches 50 kt as the PRF approaches 2000, the maximum PRF for the Radtec 43/250 radar. Section 5 discusses this as a limiting configuration due to restrictions of signal processing techniques during simultaneous Doppler and dual-polarimetric radar operations.

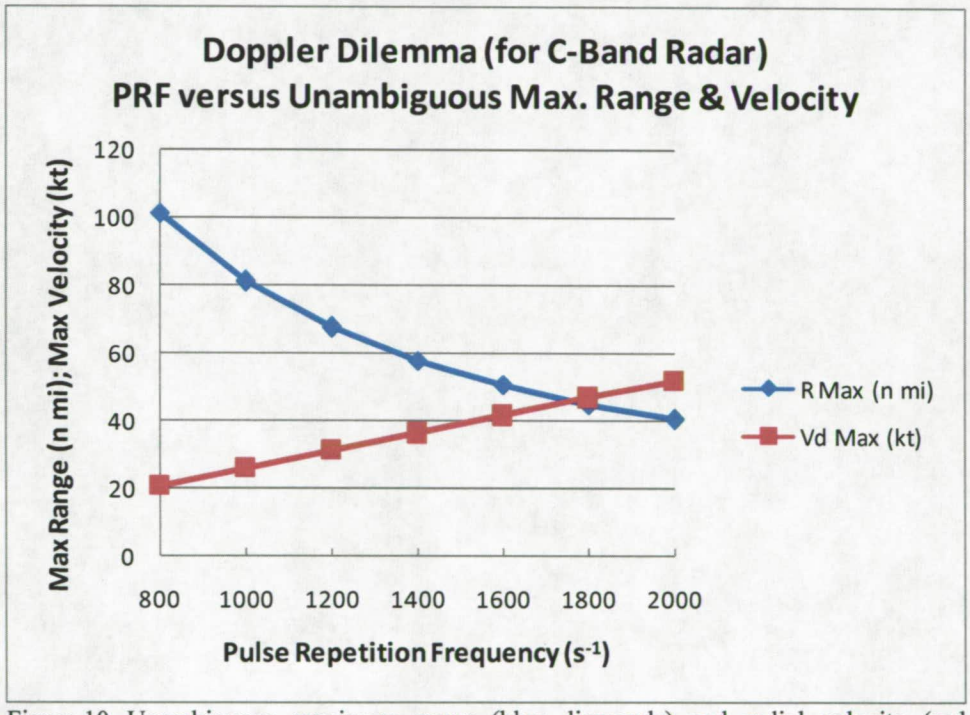

Figure 10. Unambiguous maximum range (blue diamonds) and radial velocity (red squares) versus pulse repetition frequency.

4.2 Number of Samples

For each pulse of radar energy transmitted by the radar, energy backscattered from nearby targets is sampled by the antenna/receiver system. The number of samples depends on the PRF, the antenna rotation rate and the azimuthal resolution. The rotation rate required to achieve adequate vertical resolution is 6 rpm. The standard azimuth interval for weather radars is one degree, to provide adequate spatial resolution of weather targets. Figure 11 shows the number of samples per one-degree interval as a function of the PRF, given an antenna rotation rate of 6 rpm. The number of samples recommended for estimating the Doppler radial velocity with the Radtec 43/250 is 32. Fig. 11 indicates that a PRF of about 1200 is needed to acquire 32 samples per one-degree azimuth interval, when the antenna is rotating at 6 rpm.

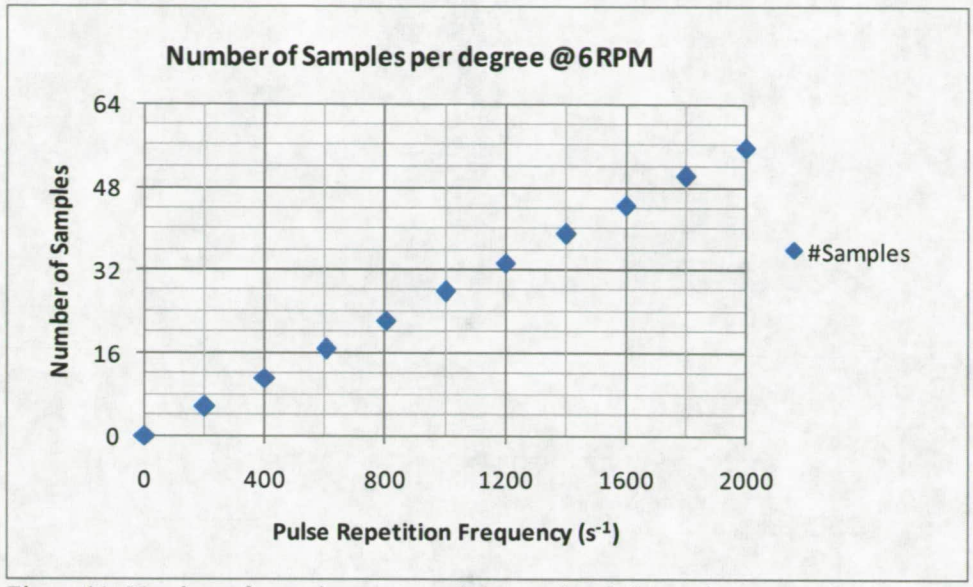

Figure 11. Number of samples per one-degree azimuth interval versus pulse repletion frequency, for an antenna rotation rate of 6 revolutions per minute.

4.3 Duty Cycle, Pulse Length, and Pulse Repetition Frequency

The radar duty cycle is defined as the fraction of time the radar transmitter is transmitting. It is determined by the pulse length and PRF. For example, a pulse length of 3 microseconds and a PRF of 1000 pulses per second results in a duty cycle 0.003. The Radtec 43/250 has a recommended maximum duty cycle of 0.003. Figure 12 shows PRF versus the maximum pulse length available for this upper limit of the duty cycle. It indicates that the transmitter can sustain a PRF of about 1200 pulses per second with a maximum pulse length of about 2 microseconds. At its maximum PRF of 2000 the maximum available pulse length is about 1.5 microseconds.

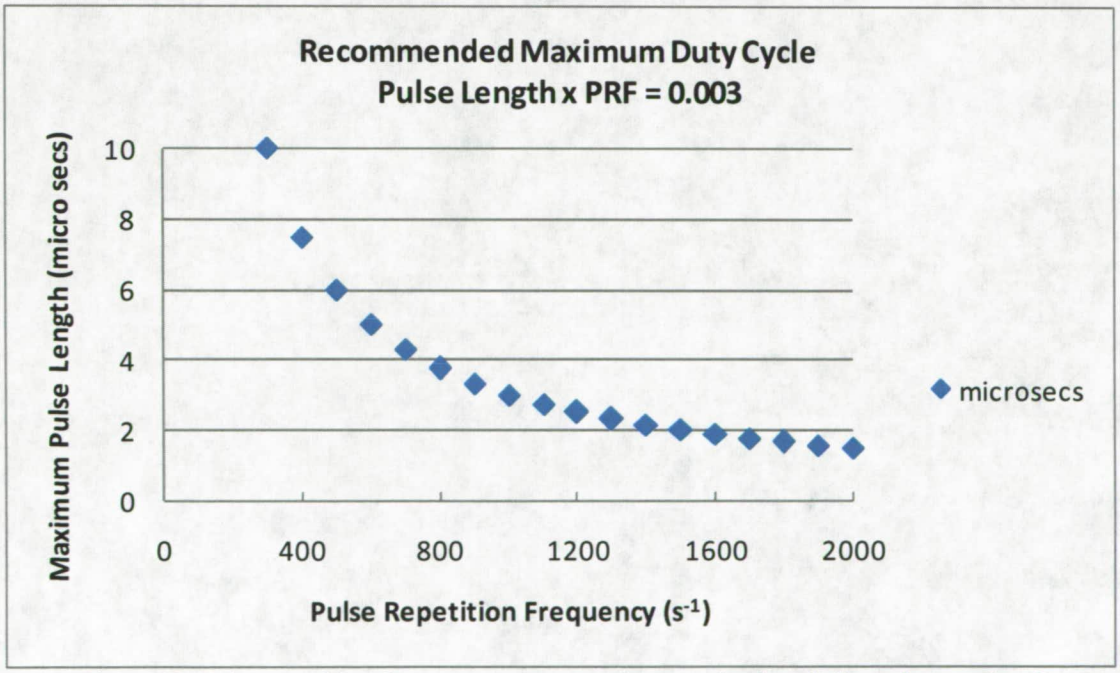

Figure 12. Pulse repetition frequency versus maximum pulse length for a duty cycle of 0.003.

4.4 Sensitivity

The pulse length affects the sensitivity of the radar to weak echoes, such as those associated with sea-breeze and outflow boundaries. Long pulses give better sensitivity; however, the minimum detectable signal increases with increasing range for all pulse lengths. Figure 13 shows range versus radar sensitivity for several pulse lengths for the Radtec 43/250. This radar has excellent sensitivity over a wide range of pulse lengths, with an ability to detect echoes as weak as -10 dBZ out to a range of at least 40 n mi, sufficient for detecting weak echoes of interest to the 45 WS.

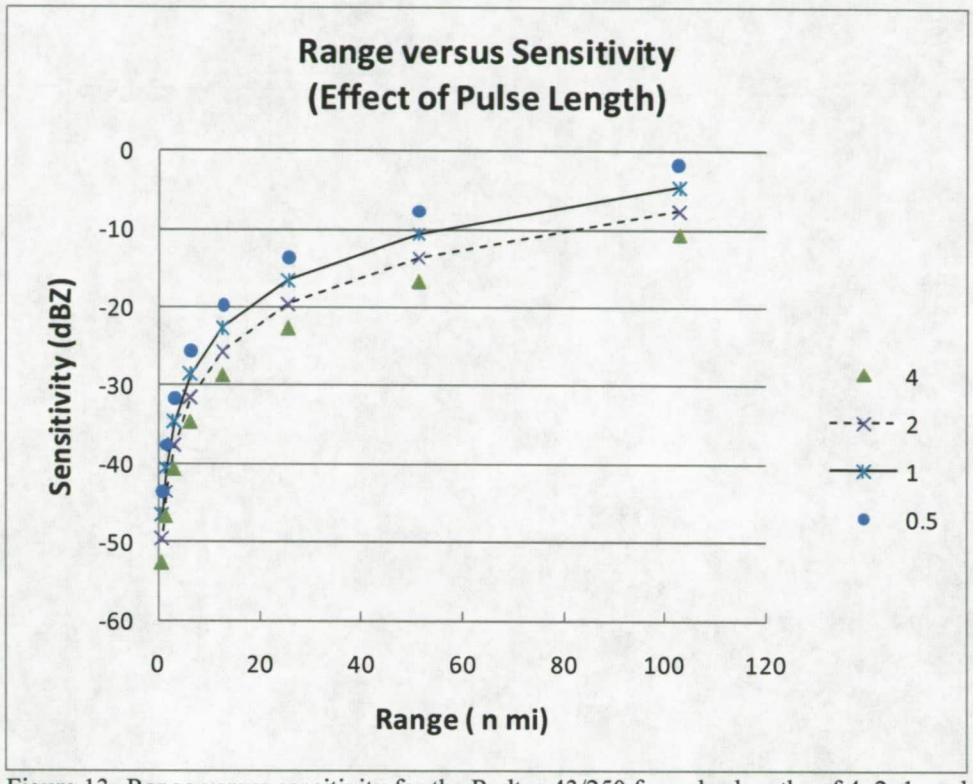

Figure 13. Range versus sensitivity for the Radtec 43/250 for pulse lengths of 4, 2, 1, and 0.5 microseconds.

5. Doppler and Dual Polarization Compatibilities

Advanced signal processing techniques are used in Doppler and dual polarization modes to improve the quality and appearance of radar products. However, the full range of capabilities of the Doppler mode are not available when the dual polarization mode is included, as outlined in Table 3 below. Nevertheless, including the dual polarization mode improves rainfall estimation and adds particle classification, an important indicator for cloud electrification and severe weather.

Table 3 provides a summary of several capabilities of the new radar under its two fundamental modes of operation: single polarization with Doppler, and dual polarization with Doppler. Radar reflectivity (dBZ) is available with both single and dual polarization. Horizontal (H) and vertical (V) dBZ data are provided in the dual polarization mode. Classification of hydrometeors as solid and liquid is the main advantage provided by dual polarization radar. Particle classification allows a more informed diagnosis of the microphysical environments associated with rain, hail, graupel and ice crystals, and the potential of the storm for generating severe weather and/or lightning. Rainfall rate estimation by dual polarization technology is improved over single polarization through differences in the reflectivity of horizontally and vertically polarized microwaves by large, deformed rain drops. Second trip echoes can be filtered automatically by advanced signal processing techniques when the single polarization mode is used, but not for dual polarization. Automated unfolding of Doppler velocities allows the useful range of Doppler radial velocity imaging to be doubled, using 3:2 pulse staggering, when in single polarization mode. The last row of Table 3 indicates that Doppler radial velocity unfolding is not recommended when the radar is in the simultaneous Doppler and dual polarization mode. This constraint confines the maximum unambiguous Doppler radial velocity to about 50 kt, because of the Doppler Dilemma discussed in Section 4.1 and shown in Figure 10. A 50 kt unambiguous Doppler radial velocity can be attained with a PRF of 2000, out to a range of about 40 n mi, as shown in Figure 10. The 50 kt upper limit would be useful because it is the threshold speed for the classification of severe weather.

Table 3. Radar compatibilities using single and dual polarization, both with Doppler radial velocity.

Parameter	*Single Polarization*	*Dual Polarization*
Particle Classification	Not Possible	Possible and Effective
Rainfall rate Estimation	dBZ only	H&V dBZ, Z_{DR}, K_{DP}, ϕ_{DP}
Second Trip Echo filter	Possible with random phasing	Not possible
Doppler Velocity Unfolding	Yes w/Dual PRF	Not Recommended

Table 4 shows three suggested configurations for the Radtec 43/250 based on the technical radar constraints discussed in Sections 4.1, 4.2, 4.3, 4.4, and 5, and operational weather considerations. The AMU recommends the 45 WS scan strategy for each configuration.

The Doppler and dual polarization mode has a high PRF and a short pulse length in order to attain a 50 kt unambiguous Doppler radial velocity, while staying within the duty cycle constraint. The range is restricted to 40 n mi by the Doppler Dilemma (Section 4.1 and Figure 10). The radar vendor, RadTec, does not recommend Doppler Velocity Unfolding when the radar is in the combined Doppler and dual polarization mode.

In the Doppler-only mode, Doppler Velocity Unfolding can be used to "unfold" Doppler radial velocities, extending their useful range to ~60 kt by a technique referred to as 3:2 pulse staggering. The 60 kt radial velocity extends well above the 50 kt threshold for severe weather.

A dual-polarization-only mode may be useful for long range detection of thunderstorm anvils, to infer hydrometeor size, phase, and possible electrification. Doppler radial velocities are not available when the radar is in the Dual Polarization only mode.

Table 4. Suggested configurations for the Radtec 43/250 radar using the 45 WS scan strategy.

Parameter	***Doppler and Dual Polarization***	***Doppler only***	***Dual Polarization only***
Pulse Repetition Frequency	2000	1200	1200
Pulse Length	1 microsecond	2 microseconds	2 microseconds
Range	40 n mi	60 n mi	80 n mi
Max Unambiguous Velocity	~ 50 kt	~ 30 kt (Up to ~ 60 kt with velocity unfolding)	N/A

6. Evaluation

Evaluation of the scan strategy for the Radtec 43/250 radar will involve three related aspects: Volume scan timing, product generation, and product display. The primary questions involve timely generation, and distribution of radar products, and ease of interpretation of radar displays by the radar operator.

6.1 Volume Scan Timing

A complete volume scan with 13 elevation angles should take approximately 2 min 42.5s with the antenna rotating at 6 rpm. If the actual time exceeds 3 min the number of elevation angles would have to be reduced to satisfy 45 WS operational requirements for an update frequency of 3 min or less. If the number of elevation angles must be reduced to 12, the two simplest solutions would be to

1) Eliminate the highest elevation angle in the 45 WS scan strategy, thereby increasing the radius of the cone of silence from 9 to 12 n mi, at 27,000 ft, but preserving the small vertical gaps over the KSC/CCAFS launch facilities; or

2) Adopt the AMU scan strategy and eliminate its highest elevation angle, thereby increasing the cone of silence from 8 to 9.5 n mi at 27,000 ft, but increasing the vertical gaps over the KSC/CCAFS launch facilities by 61%, similar to the current WSR-74C scan strategy.

6.2 Product Generation and Distribution

Timely generation and distribution of a large suite of radar products is critically important for the new radar. The radar operator currently has several tens of products (Short 2000) readily available to aid in diagnosis of evolving weather conditions and evaluation of LLCC. Data compression techniques facilitate data transmission and analysis, especially when storms are sparsely distributed. However, extensive storm coverage can slow down the product generation process. Product generation and distribution from the new radar system should be monitored over weather conditions that range from isolated to extensive storm coverage.

The new radar product suite will include Doppler and polarimetric variables, adding a wealth of information on the microphysical and kinematic environment of storms, but also requiring greater computer resources to generate in a timely manner. The generation and distribution time of new products should be carefully monitored.

6.3 Product Display and Vertical Resolution

The current report focuses on the vertical resolution provided by several candidate scan strategies. The visual appearance and accuracy of radar products must facilitate rapid and accurate interpretation by the radar operator. Radar sampling of the 3-D structure of storms, and consequently the ability to construct an accurate display from the raw radar data, depends on the vertical resolution. Vertical resolution is determined by the number of elevation angles and their vertical spacing. The number of elevation angles in the current study is constrained to be no more than 13, as explained in previous sections. The vertical resolution resulting from the scan strategy recommended in this study (45 WS) has a range dependence different from the WSR-74C strategy currently in operational use.

For example, the vertical resolution of radar products affects evaluation of LLCC and monitoring of developing storms during routine daily operations. Vertical cross sections of radar reflectivity are used to identify the potential for lightning in individual developing storms, affecting the subsequent issuance of lightning advisories and warnings. One lightning-threat criterion that was developed locally within the 45 WS concerns 30 dBZ values within storms that reach the altitude of the -10C isotherm (Roeder and Pinder 1998). Figure 9 indicates that vertical gaps at an altitude of 27,000 ft associated with the recommended 45 WS scan strategy vary from 6000 ft to ~2000 ft, over the range of 10 to 18 n mi from the radar. This strong range dependence may affect the representation of the vertical structure of storms, required for accurate interpretation of their intensity and potential to generate lightning.

The AMU recommends products sensitive to vertical resolution be compared to similar products from nearby radars. These could include the WSR-88D at NWS MLB, and the WSR-74C at PAFB if it is operating concurrently with the new radar.

7. Summary and Conclusions

The Radtec 43/250 radar is expected to provide significant improvements in radar remote sensing of convective storms over the launch and landing facilities of KSC/CCAFS. The Doppler mode of operation will provide near real-time detection of storm-generated convective winds and monitoring of potentially tornadic low-level circulations. The dual polarization mode will allow hydrometeor classification within developing storms, aiding in identification of electrification processes and evaluation of LLCC.

Operational requirements for high vertical resolution data updates every 3 min or less over the KSC/CCAFS launch and landing facilities can be met by rotating the antenna at 6 rpm and using 13 elevation angles. The recommended scan strategy, proposed by the 45 WS and refined by the AMU, provides a 33% reduction in vertical gaps compared to the current scan strategy of the WSR-74C. Two alternative scan strategies were compared: one provided by Radtec Engineering, Inc. in response to initial 45 WS guidelines, and one patterned after the current WSR-74C strategy with one additional elevation angle. The comparison between the three scan strategies showed that each was able to meet at least one of the 45 WS requirements outlined in Section 1.1, but attaining vertical gaps less than 2250 ft at an altitude of 27,000 ft that were also independent of range was not possible. Nevertheless, the 45 WS scan strategy documented above provides a significant improvement over the current WSR-74C scan strategy, especially over the space launch and landing facilities of KSC/CCAFS.

The new radar will be located west of the KSC/CCAFS complex in an area where developing storms are found frequently. Storms that develop directly over the radar will be missed because they will be within the radar's cone of silence. This problem, which affects most radars, can be mitigated by using data from a nearby radar, in this case the WSR-88D at NWS MLB. The vendor-provided radar processing software has an option for blending data from another radar data to fill in the cone of silence. This option should be explored to determine the degree of complexity and effort required for its implementation.

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List of Acronyms

3-D	Three Dimensional
45 WS	45th Weather Squadron
ϕ_{DP}	Differential Phase Shift
AMU	Applied Meteorology Unit
CCAFS	Cape Canaveral Air Force Station
dBZ	$10 \times \text{Log}_{10}(Z_e)$
GHz	gigahertz
Horizontal	H
K_{DP}	Specific Differential Phase
KSC	Kennedy Space Center
Z_{DR}	Differential Reflectivity
Z_e	Equivalent radar reflectivity
PAFB	Patrick Air Force Base
LLCC	Lightning Launch Commit Criteria
NWS MLB	National Weather Service, Melbourne
PRF	Pulse Repetition Frequency
rpm	revolutions per minute
WSR-74C	Weather Surveillance Radar model 74C
WSR-88D	Weather Surveillance Radar model 88D
Vertical	V

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14. ABSTRACT

The 45th Weather Squadron (45 WS) is replacing the Weather Surveillance Radar, Model 74C (WSR-74C) at Patrick Air Force Base (PAFB), with a Doppler, dual polarization radar, the Radtec 43/250. A new scan strategy is needed for the Radtec 43/250, to provide high vertical resolution data over the Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) launch pads, while taking advantage of the new radar's advanced capabilities for detecting severe weather phenomena associated with convection within the 45 WS area of responsibility. The Applied Meteorology Unit (AMU) developed several scan strategies customized for the operational needs of the 45 WS. The AMU also developed a plan for evaluating the scan strategies in the period prior to operational acceptance, currently scheduled for November 2008.

15. SUBJECT TERMS

Radar, Weather Radar, Weather, Meteorology, Instrumentation, Sensor, Remote Sensing, Space Shuttle

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